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FORMATION AND EMISSION OF NITROGEN OXIDE IN GAS TURBINE ENGINES: PLUME EFFLUENT CHARACTERISTICS OF TF30-P111+ AND TF33-P9 ENGINES

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13. ABSTRACT (*Maximum 200 words*)

Phase I of this project focused on the creation of a spatial emissions map of the plume effluent in the exhaust stream directly behind the engine in a jet engine test cell (JETC). Both afterburning TF30-P111+ and non-after-burning TF33-P9 engines were tested. Measurements were taken in conjunction with actual engine tests for validity of the data. Temperature, oxides of nitrogen (NO_X), carbon monoxide (CO) concentration, and velocity were among the characteristics measured radially and axially in the plume for each engine type. The main focus of this study was on NO_X, consisting of nitric oxide (NO) and nitrogen dioxide (NO_2).

Measurements in the P111+ plume reveal levels of NO_x above 300 ppm along the centerline of the effluent. A dip in the NO_X emissions at afterburner shows signs of a reburning and/or dilution effect by the atmospheric combustion in the effluent. Significant amounts of NO_2 are present in the effluent over the entire power range. Temperatures at military power reach 1100°F along the centerline, and CO values are below 80 ppm. Carbon monoxide concentrations decrease from idle to military power (full power, no afterburner), then rise sharply in afterburner. The CO peaks shift outward from centerline as do the temperatures due to the radial geometry of the afterburner combustion (over 10 percent CO at 2850°F).

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An area-weighted NO_x index shows that power settings above military power account for 75 percent of the JETC emissions.

The P9 plume is more uniform than the P111+ due to a narrow, fixed nozzle and the lack of fan air in the post-turbine section. NO_X levels only reach 120 ppm at full military power with temperatures of 820°F. Dilution of the effluent by room air is more prevalent due to the longer axial sampling distance and the slower flows.

PREFACE

This report was prepared by the Combustion Laboratory at the University of California at Irvine, Irvine, CA 92717-3550 under Contract No. F08635-90-C-0100, from the U.S. Air Force Engineering and Services Center, Environics Division (HQ AFESC/RDVC), Tyndall Air Force Base, Florida 32403-6001.

This report summarizes the work done between 1 November 1993 and 17 December 1993, under the direction of Professor G. Scott Samuelsen and Dr. William A. Sowa. Dr. Joseph D. Wander was the Air Force project officer for this contract.

We wish to acknowledge and thank Gunnery Sgt. Plunkett and Staff Sgt. Tarazon at El Toro Marine Corps Air Station CA as well as Ms. Jeannie Warnock and Mr. Steve Thomas at McClellan Air Force Base CA for their efforts to provide for our testing in their facilities.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

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EXECUTIVE SUMMARY

A. OBJECTIVE:

The objective of this effort was to examine chemical and transport processes behind an operating jet engine as a means to explore the practicability of using selective non-catalytic reduction (SNCR) as a technology to control the oxides of nitrogen (NO_x) emissions during stationary test firing of reworked, repaired, or suspect aircraft jet engines. NO_x emissions include nitric oxides (NO) and nitrogen dioxides (NO_2).

B. BACKGROUND:

Under provisions of the Clean Air Act Amendments (CAAA), the historical (implied) exemption from NO_x emission standards of jet engines, both as a mobile source in operation and as a stationary source during static firing tests (as in test cells and hush houses), is experiencing serious scrutiny. A recent expansion in the list of cities not in compliance with ozone standards raises a possibility that, if adequate NO_x control methods are not identified, flight and maintenance operations are at risk for regulatory restrictions.

Most conventional NO_x control technologies appear incompatible with the requirements imposed by the test cell environment: variable temperature and flow rate, intolerance of significant (*i.e.*, tenths of an inch of water) pressure drops across the control system, and extreme mechanical stresses in the regions of the cell in which temperatures are high enough to support the processes. SNCR, which simply injects a reducing agent into a hot region of the postcombustion gas stream, satisfies the environmental requirements, and could be a practical technology to develop for this application if selective activation of strategically placed nozzles provide adequate mixing to complete the reduction chemistry before the gases cool in the downstream portion of the cell.

C. SCOPE:

This portion of the NO_x formation and control program details the characterization of properties of the exhaust behind TF30-P111+ (F-111 fighter) and TF33-P9 (KC-135 transport) aircraft jet engines during static test firing in a test cell at McClellan AFB CA.

D. METHODOLOGY:

A multipoint sampling probe (rake) and a single-point pitot probe were affixed to a three-dimensional traverse mounted on a rigid support and placed in the exhaust stream directly behind a jet engine mounted in the test cell. The pitot probe measured velocity. The rake measured temperature and collected exhaust gases, which where dried by cooling the transport tubing in an ice bath, and analyzed with a combination of on- and off-line systems: a Horiba chemiluminescent analyzer (NO and NO_x), a Horiba PIR 2000 nondispersive infrared analyzer (carbon monoxide), a MEXA automotive analyzer (hydrocarbons and oxygen), and a Hewlett-Packard 5890 Series II gas chromatograph equipped with a HaySep DB packed column and a thermal conductivity detector (oxygen and carbon dioxide).

E. TEST DESCRIPTION:

Sampling was conducted on an as-available, noninterfering basis from the exhausts of in-service engines as they were evaluated in the test cell before or after repair or maintenance had been performed. Before the firing of an engine on the test stand, the traverse was stepped to one of three (P111+) or two (P9) positions along the axis of the exhaust flow and fixed there for the duration of that engine test. The probes were allowed to equilibrate for 30 seconds at each of the engine power settings before sampling. The combination of rake positions and traverse settings created a horizontal array of sampling points from the center of the stream to one edge. Radial symmetry was assumed in casting the exhaust profile as a cylinder of rotation of this cross-section.

F. RESULTS:

NO and NO_x concentrations increase from idle to full military power. NO appears to be selectively removed at afterburner (AB) settings of the P111+ engines. Carbon monoxide (CO) concentrations are moderate at idle (~80 ppm), but fall off rapidly to full military power. Increasing settings of the AB (P111+) cause a drastic increase in CO levels, to nearly 1000 ppm at full AB. Engine temperatures increase with increasing power setting.

G. CONCLUSIONS:

At low power settings, which are relatively minor producers of NO_x, the exhaust temperatures are too low to sustain the chemistry of SNCR. However, at full military power and (for the P111+ engine) AB levels, which are the main NO_x-producing conditions, both the

concentration of pollutant and the exhaust temperature are high enough to be compatible with practical application of SNCR *if the mixing processes can be matched to the available residence time*.

H. RECOMMENDATIONS

Computational modeling of the application of SNCR to this system will be performed as the final stage of this effort. If the modeling results are favorable, a program of experimental verification should be performed as expediently as possible.

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SECTION I
INTRODUCTION

Photochemical oxidant, better known as smog, has been an important area of research during the past three decades. The main contributors to this problem are all forms of combustion sources (*i.e.*, automobiles, aircraft, boilers, power plants). Oxides of nitrogen (NO_x), which include nitric oxides (NO) and nitrogen dioxides (NO_2), are produced by combustion and are released into the atmosphere, in which they react to form smog.

California has led the way in regulating the pollution being produced by combustion sources operating within the state. Due to the nature of their steady power levels, stationary sources have been a major target for the Environmental Protection Agency (EPA) for emissions reduction. Recently, these stationary sources have come to include Air Force jet engine test cells (JETC), in which repaired engines are run before reinstallation on the aircraft. Though presently unregulated while on the aircraft, these engines may be required to meet local, state, and federal emission regulations for stationary combustion sources while operating in the test cells and in service.

A. GOALS AND OBJECTIVES

This study represents part of a larger program whose focus lies in the control or removal of NO_x emissions from JETCs through the use of a control strategy external to the engine. The goals for the present study are to (1) measure the exhaust plume characteristics for both an afterburning and a non-afterburning engine and (2) characterize temperatures, major gas species (including NO_x concentrations), and other characteristics at normal JETC operating conditions. The following objectives were established:

1. Design, construct, and set up a sampling traverse and probe that can collect gas samples at multiple points in the exhaust stream in the JETC;
2. Analyze the exhaust stream characteristics including emissions, temperature, and velocity; and
3. Develop an appropriate direction for future study to determine the best NO_x control method for the conditions observed.

B. BACKGROUND

Approximately 250 JETCs operated by the U.S. Air Force are considered stationary sources by the EPA (Reference 1). While they continue to be unregulated, JETCs can earn pollution credits for using control technologies to cut down on the emissions (emissions control equipment is nonexistent). Programs such as this one are working towards determining control options for existing JETCs.

JETCs provide a uniform environment in which to test an overhauled or repaired engine before it is reinstalled in the aircraft. During a test, the engine is run over its full range of power settings seen during a typical operational cycle. The major diagnostics of the engine are monitored and checked at various points during the test to see that they fall within specifications. Total time on the stand can vary depending on the condition of the engine.

Test cells vary from site to site, but a representative configuration is shown in Figure 1. The test cell is generally constructed of steel or concrete. The engine is securely mounted on a steel stand located inside either a U or L-shaped enclosure. The intake air enters through a series

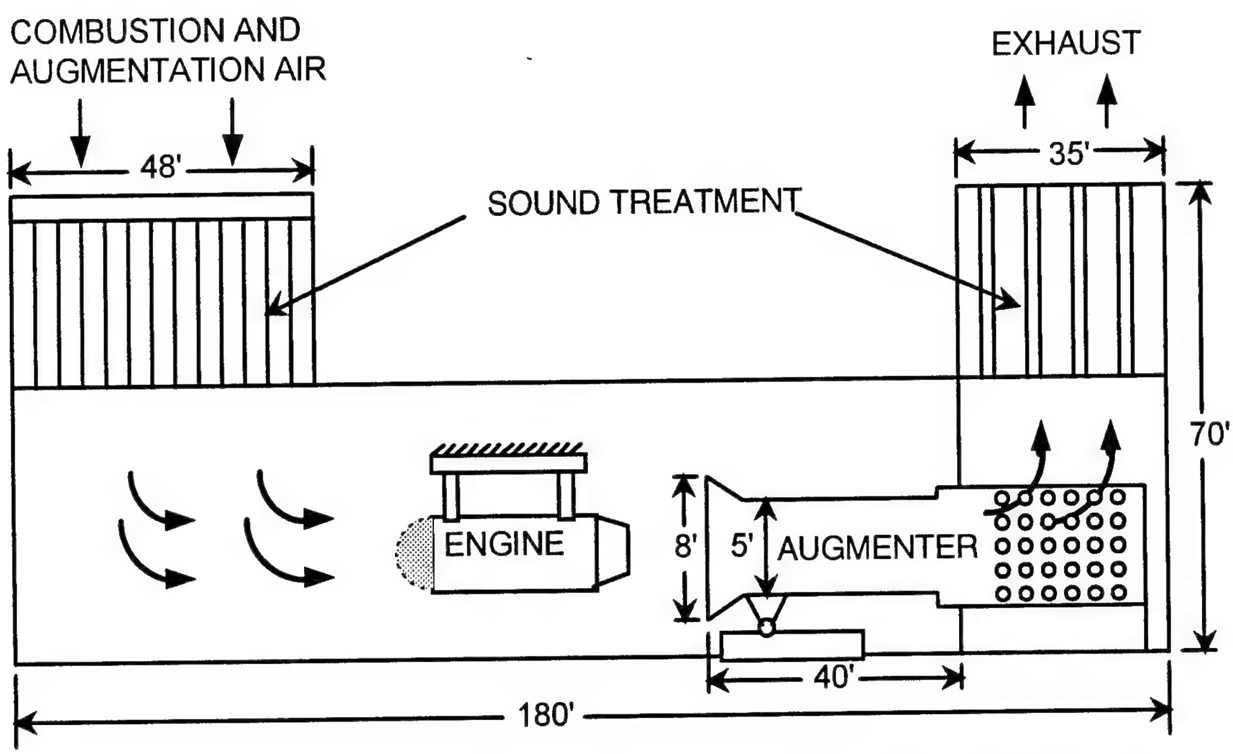


Figure 1. McClellan AFB JETC for TF30 Engines (Dimensions Approximate).

of sound-deadening baffles into the front of the cell. The engine exhaust is directed through a large, bell-mouthed opening into a long tube (known as an augmenter) that carries the exhaust into the blast room. Here, the exhaust escapes through a series of baffles in the tube and exits through the stack to the atmosphere. The construction and large scale of the intake and the exhaust of the cell are very important to prevent adverse pressure gradients within the JETC during testing that could affect the trim of the engine.

Many features are unique to JETCs. At full military and full afterburner loads, a typical test cell can process as much as 600 pounds of air per second (Reference 1). Compared with other stationary sources, JETCs spend much of their operating time in transition from one power extreme to the other, putting high demands on any candidate NO_x control technology. To control a true stationary source, one would look toward improving the combustion characteristics in the combustor area, in which most of the pollutants originate. Since this would defeat the purpose of the JETCs, a solution (or solutions) must be sought external to the engine. This may require some type of control based on engine speed.

Many strategies for reducing emissions and NO_x in JETCs have been tested, *e.g.* reburning, fuel additives, etc. (References 1-11). Near-steady-state applications have used catalytic beds or selective catalytic reduction (SCR), with good success. However, application of SCR in JETC facilities is expected to be difficult and expensive, at best. Another process known as selective noncatalytic reduction (SNCR) has shown much promise for NO_x control (References 6, 12-13). This method involves injecting an additive downstream of the actual combustion process and allowing it to mix and react with the hot exhaust gases to reduce the final NO_x concentrations. Unlike SCR, in which the flow goes through the same catalytic process throughout the power cycle, SNCR allows for tuning of the additive injection via a control system to tailor the proper amount of additive as conditions change. In both cases, the following conditions must be met for proper reduction to occur:

- Temperatures must be sufficient (*i.e.*, >1500°F for NH_3 injection) and relatively isothermal,
- Increased CO concentrations can help lower the necessary reaction temperature,
- Residence time at the proper conditions must be sufficient, and
- Oxygen must be in excess.

To fully optimize this procedure, we must understand the composition of the gases exiting, in this case, the jet engine in the test cell.

The area of interest for this study lay in the area between the nozzle of the engine and the entrance to the augmenter. The augmenter serves three purposes (Reference 1):

1. The bell-mouthed opening of the augmenter, similar in shape to an ejector pump, draws air into the test cell to ensure equal pressure at the inlet and exit of the engine;
2. Part of the air drawn into the augmenter flows around the engine housing to provide cooling similar to that experienced in the aircraft; and
3. The air drawn into the augmenter dilutes and cools the hot exhaust gases to help prevent damage to the material within the JETC.

To cool the gases further before they are released into the atmosphere, water may be injected into the exhaust stream at various stages downstream of the augmenter mouth. Since SNCR depends on chemical reactions occurring at high temperatures in near-isothermal conditions, it is important to determine the conditions in the hottest part of the flow before the mouth of the augmenter.

C. SCOPE AND APPROACH

The program guiding this research encompasses two main areas of study:

Phase I: characterizing the JETC effluent at the engine nozzle exit, and

Phase II: modeling of JETC conditions at UC Irvine to evaluate candidate NO_x control strategies.

As stated in Section IB, this report documents the completion of the first phase. An actual JETC is used to provide realistic data sets which map out the exhaust characteristics of the engines being tested under normal operation profiles. This involves sampling in the exhaust stream within two diameters downstream of the engine nozzle exit. The approach taken involves the following objectives:

- The design, construction, and setup of a sampling traverse and probe capable of taking gas samples at multiple points in the exhaust stream in the JETC;
- The analysis of exhaust stream characteristics including emissions, temperature, and velocity; and

- The development of an appropriate direction for Phase II research based upon Phase I findings.

The next section will discuss the apparatus as outlined in the first objective. Sections III and IV will address the remaining objectives.

SECTION II
EXPERIMENT

The experiment for the Phase I research consisted of collecting and analyzing exhaust samples for species composition, temperature, and velocity. Two engines were tested using a multipoint sampling probe and a single-point pitot probe to measure the exhaust samples and velocity, respectively. A traverse was constructed to hold the probe securely and allow for three-dimensional movement within the flow. A combination of both on- and off-line instrumentation analyzed the gas flows for their composition and characteristics. McClellan Air Force Base CA was chosen as the site for this research.

To insure as few problems as possible during the actual testing period, preliminary testing was performed in a JETC located at El Toro Marine Corps Air Station CA. A General Electric F404 turbofan engine with afterburner (17,000 pounds thrust) was used in the testing to examine the following issues:

- The structural integrity needed for the sampling probe to withstand high temperature flows seen at full afterburner conditions,
- The possible designs for a probe-holding device that would provide the greatest amount of rigidity, and
- The approximate emissions, temperatures, and velocities to be expected.

This testing proved invaluable to the development and success of the final sampling traverse and probe configuration.

A. THE ENGINES

McClellan AFB serves as a depot for the repair of F-111 and KC-135 aircraft engines. Both aircraft use Pratt and Whitney engines as their power plants. The TF30-P111+ model is an afterburning engine used in the F-111 fighter. This turbofan ducts all of its bypass fan air into the afterburner section. It develops 25,000 pounds of thrust while consuming almost 54,000 pounds of fuel per hour at full afterburner. Typical engine run throttle positions and engine characteristics are noted in Table 1. The nozzle is of a converging-diverging configuration consisting of an inner and outer nozzle. The inner nozzle is controlled while the outer nozzle

TABLE 1. TYPICAL ENGINE SPEEDS AND FUEL FLOW RATES

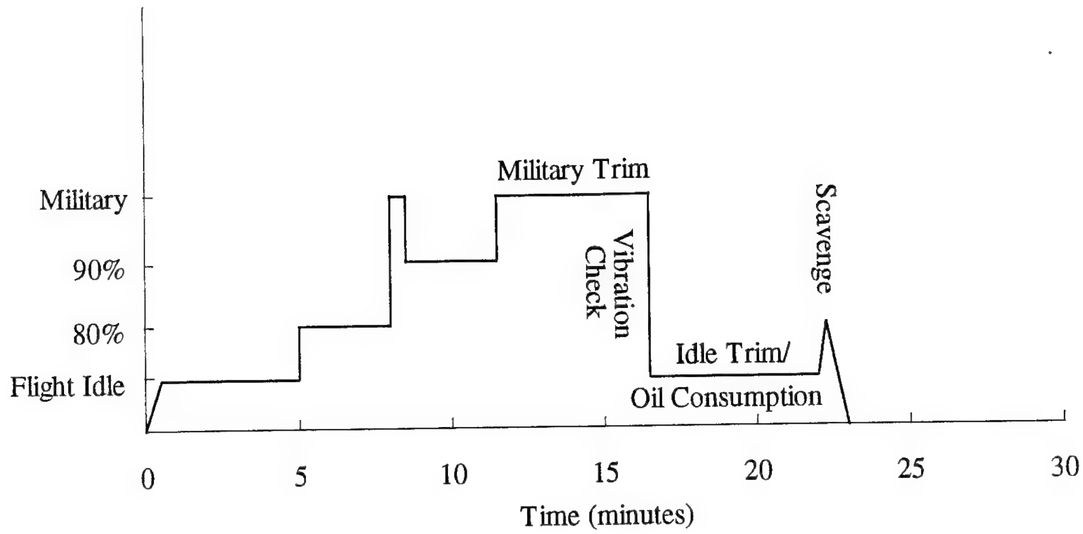
	TF30-P111+				TF33-P9		
Throttle Setting	Turbine (%)	Turbine (RPM)	Fan (RPM)	Fuel (lb/hr)	Turbine (%)	Turbine (RPM)	Fuel (lb/hr)
Flight Idle	66.1%	10100	4300	1152	58.6%	5706	1790
80% Power	79.9%	12300	6700	3104	--	--	--
Military -10" Power	89.1%	13700	8500	6543	--	--	--
90% Power	90.3%	13800	8700	7077	90.1%	8774	4848
Data-Set Power	--	--	--	--	92.2%	8974	5049
Military -6" Power	91.1%	14000	8800	7403	95.3%	9274	6993
Part Power	--	--	--	--	96.4%	9381	7206
Military Power	94.6%	14500	9500	9402	100.0%	9733	8773
Zone 1 Afterburner	94.6%	14500	9400	13944	--	--	--
Full Afterburner	94.1%	14400	9300	53788	--	--	--

works on aerodynamic effects. The inner nozzle radius is 13 inches through military power (full power, no afterburner) and 18 inches at full afterburner.

A typical run schedule for an engine mounted in the test cell is intended to check critical specifications (*i.e.*, speeds, temperatures, pressures) and trim the engine as necessary. For example, a complete test for a TF30-P100 series engine consists of two different run schedules as shown in Figure 2. The different power settings and checks are defined as follows:

- Flight idle is the minimum power setting;
- The 80- and 90-percent power settings are based upon the turbine shaft speed;
- Military minus 10 inches and Military minus 6 inches powers are based upon engine pressure ratio;
- Military power is full power without afterburner;
- Zones 1 through 5 denote the spray-bars as they are activated in the augmenter section of the engine (behind the turbine) during the afterburner stages with Zone five denoting full afterburner power; and
- Scavenge involves a short burst of power before shutdown.

Preliminary Run



Performance Run

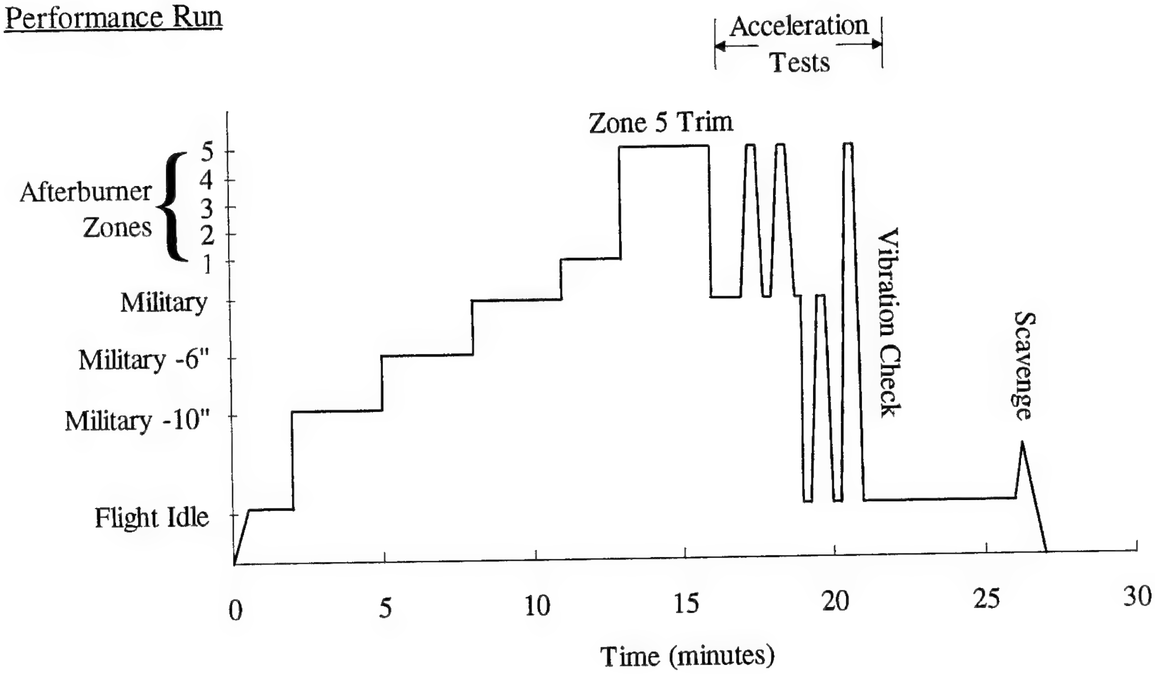


Figure 2. Typical TF30-P111+ Preliminary and Performance Run Schedules at McClellan AFB

The TF33-P9 non-afterburning engine is used on the KC-135 transport. Its 17,000 pounds of thrust are developed mostly by its high-bypass turbofan that is ducted outside the engine casing through a cowling. Instead of concentrating on power as does the P111+, the focus of the P9 is on fuel economy, using only 9500 pounds of fuel per hour at military power. The radius of the exhaust nozzle on this engine is fixed at 12 inches. Its power settings are similar to the non-after-burning positions of the P111+ engine, with the addition of two powers:

- Data-set power is used to collect necessary information for proper engine evaluation, and
- Part power is a typical cruising speed.

Typical McClellan AFB runs call for extended periods of running at each of these positions with occasional cool-down periods at flight idle.

B. EXPERIMENTAL APPARATUS

The apparatus used to conduct the experiments consists of two probes mounted to a traverse. The sample probe was designed from 3/4-inch stainless steel (SS) pipe in a reverse double triangle configuration (Figure 3). The five sampling points map a radial emissions profile from the engine centerline to the edge of the flow field. This arrangement assumes radial uniformity of the flow field. At each axial station, sample is drawn in through 1/8-inch SS tubing inside the 3/4-inch probe tip shown in the expanded section in Figure 3. A Type R open-junction thermocouple is also run through 1/8-inch SS tubing in a 3/8-inch probe tip located on top of the sampling probe. All 1/8-inch tubing is run through the main vertical leg of the probe until exiting via a manifold at the base of the probe. The entire assembly is water-cooled.

A Dwyer 5/16-inch pitot probe is used to make velocity measurements, which are used to predict residence time of the flow before it enters the augmenter section. The vertical part of the

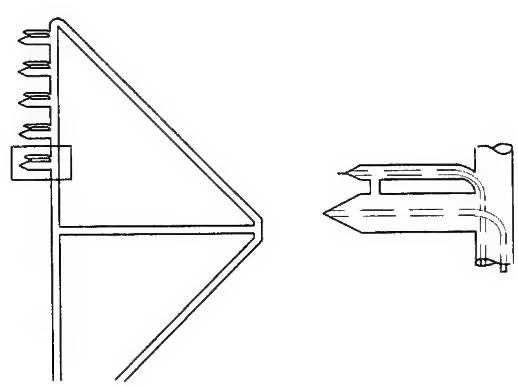


Figure 3. The Sampling Probe

probe is run inside 3/4-inch SS pipe that triangulates backwards in a fashion similar to the sample probe while the remainder of the probe is left exposed. The pitot probe assembly can be attached and removed from the main probe using bolt-on clamps.

The traverse is designed with strength and rigidity in mind as well as flexibility of probe positioning. The frame is constructed from 3-inch box-tubing extending 100 inches in length by 50 inches in width by 48 inches in height (Figures 4 and 5). The traverse sits well below the hot flows of the jet exhaust. The stand is leveled and bolted to stand-off plates, which are bolted securely to the ground. Its design allows the probe to be moved in X-, Y-, and Z- directions. Both X and Y directions use T-rails and pillow blocks for positioning the probe with clamps to hold the traverse fixed. The X-direction positions the probe axially in the flow while the Y- and Z-directions are for initial centering of the probe. Radial points are measured from the engine centerline (Z = 0.0 inches) to the edge of the flow field (Z = -14.75 inches).

C. EXPERIMENTAL MONITORING AND PROTOCOL

The nature of the sample probe design lends itself to quick quenching of the sample flow. To ensure a "dry" sample, a PVC water drop-out in an ice bath is used immediately following the exit of the sample lines from the sample probe. Teflon™ 1/4-inch tubing carries the sample to the on-line analyzers. Two pumps using stainless steel bellows draw the gas to a manifold of valves that allows one sample leg to go to the analyzers while the other four legs are directed into a dump line. A Magnahelic pressure gage is used to measure the differential pressure from the pitot probe.

The gas species of major concern for this testing include NO, NO_x, carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2). Unburned hydrocarbons (HC) are also monitored. NO and NO_x are measured using a Horiba chemiluminescent analyzer calibrated on a 488 ppm NO span gas in nitrogen. A Horiba PIR 2000 nondispersive infrared analyzer measures CO concentrations calibrated on a 102-ppm span bottle. Both instruments are calibrated at the beginning of each engine run. The calibration holds to within ± 5 percent during the course of each run. HC and O_2 are measured using a MEXA Automotive Analyzer spanned on 848 ppm of bottled HC at ambient O_2 (20.91 percent).

A Hewlett-Packard 5890 Series II gas chromatograph equipped with a HaySep DB packed column and a thermal conductivity detector is used to measure O_2 and CO_2

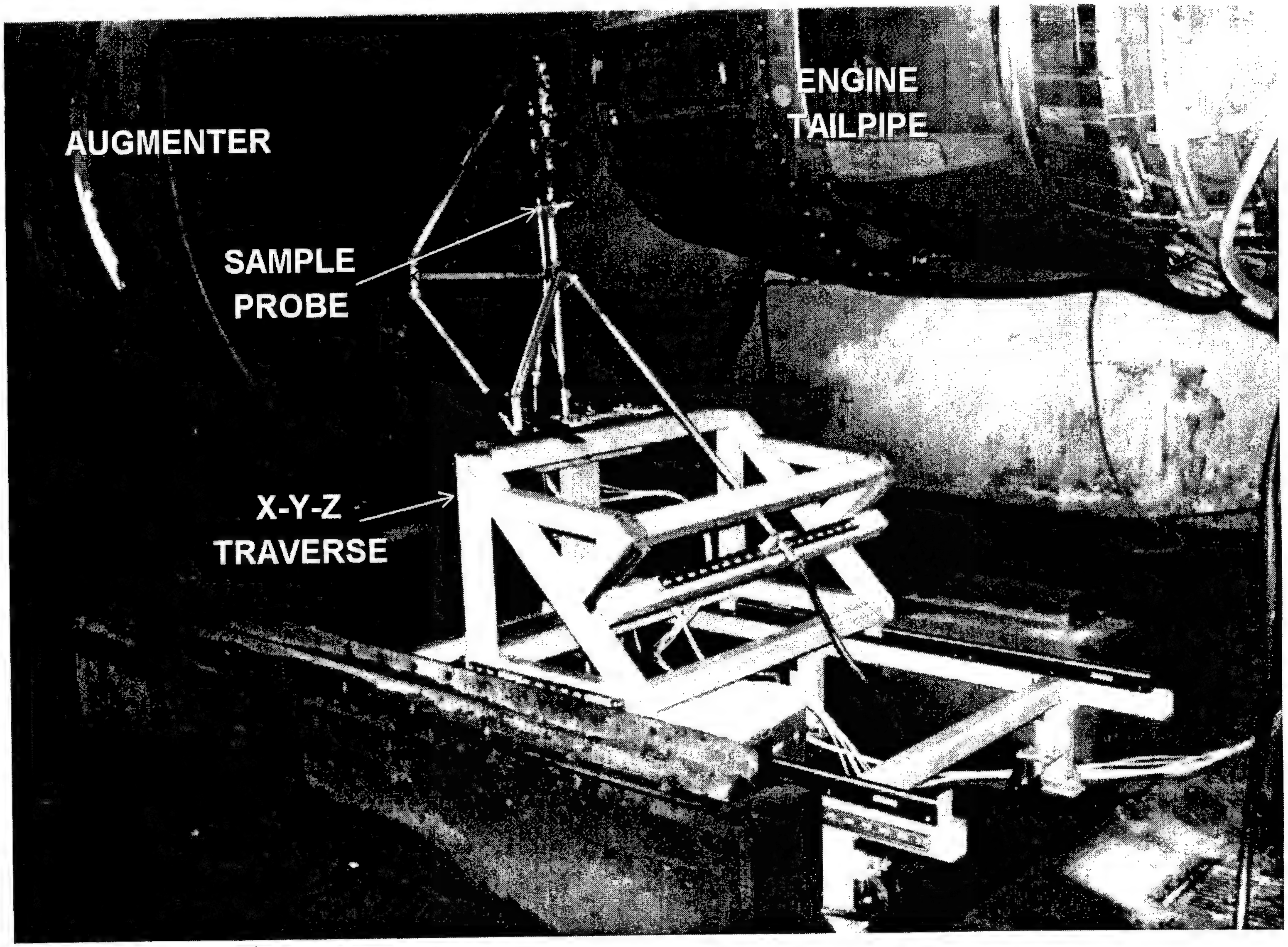


Figure 4. The Sampling Probe, Traverse, and JETC Orientation

concentrations. Samples are collected in Teflon™ sample bags for later measurements using the chromatograph. An automated valve with a sample loop in the GC allows for accurate dispensing of the sample. Calibration is performed using a span gas of 19.2 percent O_2, 4.6 percent CO_2, and a balance of N_2. Measurements were repeatable within ± 3 percent.

A sampling grid was created for this experiment, based on the radial profile of the sampling probe and the extremities of X-traverse. For the P111+ engine, samples were taken at the exit of the exhaust nozzle (X = 0.0 inches), at the furthest downstream point allowed by the augmenter (X = 21.5 inches), and halfway between (X = 10.75 inches). The augmenter on the P9 test stand was located further back from the exhaust exit allowing for sampling at X= 36.5 inches away from the exhaust exit as well as at X = 0.0 inches.

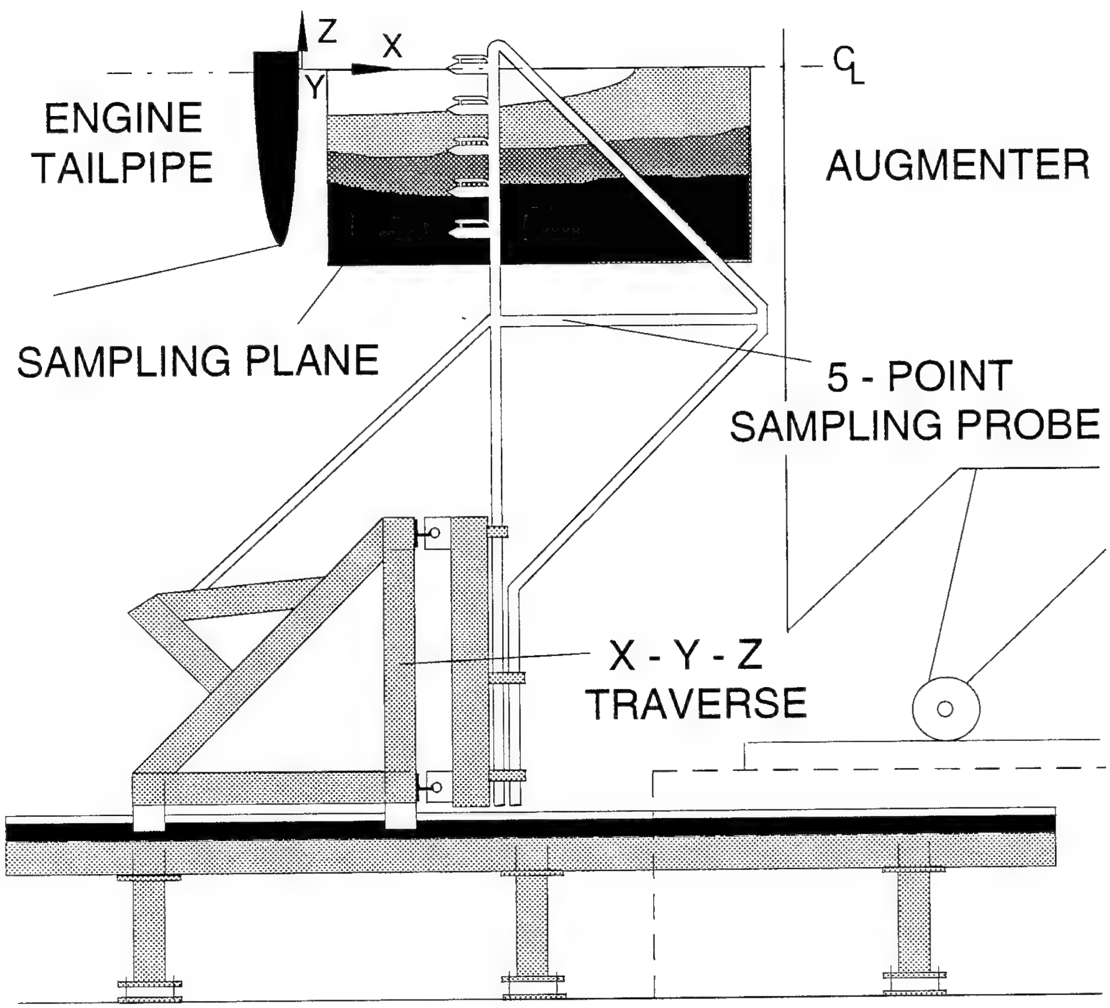


Figure 5. The Traverse and Sampling Plane

Calibration of the instruments was performed before the beginning of each run. Measurements were made over an entire engine run, holding the probe position fixed. Once a condition was reached, 30 seconds were allowed for the condition and the instruments to stabilize before readings were taken. Testing was performed in parallel with normal test cell activities. The points measured at each downstream position were taken during the course of one engine testing cycle. Therefore, the data in the following results reflect the collection of many data points from many different engines. Data taken at similar power conditions for each engine were averaged to get a final emissions value at each sample point.

Measured values were generally repeatable from engine to engine. Mass balances were not completed on the measurement results. There exist several sources of error in attempting a mass balance on the engines:

- The measured data must be spatially averaged from several different engines in varying conditions to complete the mass balance. A mass-weighted averaging approach cannot be used due to lack of necessary data.
- Different day-to-day ambient inlet temperatures and pressures alter the performance of each engine during the run,
- The fuel used for the tests is a blend of JP-4, -5, and -8 that varies in composition (all serviced aircraft have their tanks drained and are combined into the JETC tank),
- Each engine is trimmed differently to meet the given ranges at each power band, thus resulting in slight engine-to-engine variation,
- Airflow into the engine is not measured. It must be extracted from curves using the fan speed to calculate the available air,
- Fuel flow to the engine was monitored using a bulk flow reading for which calibration curves were not available,

For these reasons, mass balances were not completed.

SECTION III
RESULTS

A two-dimensional sampling plane is defined radially from centerline to the extent of the flow and from the exit of the exhaust to the mouth of the augmenter (Figure 5). For the P111+ contour plots, linear interpolation with a second-order smoothing of the data is used to generate the contours seen in Figures 6 through 11. The data set is derived from averages of experimentally measured data (Appendix A). A typical data-field is based on the sampling points indicated by open circles in the plots. In all cases, radial uniformity of the flow is assumed.

A. NO/ NO_X EMISSIONS

The plots shown for NO and NO_x (Figures 6 and 7, respectively) show similar trends; thus, unless otherwise specified, NO_x data will be referred to for the general case. Strong gradients towards the exhaust plume centerline (Z = 0.0 inches) are seen through military power. The slight positive slope shows some signs of dilution from the ambient room air towards the centerline, but the effects are not significant enough within the resolution of the curve fitting. The area-weighted NO_x concentrations increase from 7.4 to 137 ppm (parts per million) as the power increases through military power, peak NO_x values exceeding 300 ppm along the centerline. At full afterburner, the values at the extent of the flow field (Z = -14.75) are seen to be much higher than at the lower throttle settings. This can be explained as a result of the inner nozzle opening, causing a spreading of the flow field shown in Figures 6h and 7h.

Zone 1 afterburner experiences a dip in the point NO and NO_x emissions made evident in Figures 6g and 7g, respectively. Since the reaction seen in the afterburner is closer to atmospheric pressure, it acts as a reburner, breaking down NO from the combustor. However, nitrogen dioxide (NO_2) concentrations rise significantly relative to NO suggesting oxidation of the nitric oxide in the hot gas stream. The result is a steady increase in the NO_x levels through full afterburner when an area-weighted average of the NO_x values is taken (Table 2).

Table 2 also shows the normalized index for NO and NO_x. This index is proportional to an emissions index for comparison purposes (Appendix A). The NO_x index climbs until it reaches its peak at military power. Afterburner levels drop off significantly due to the high fuel

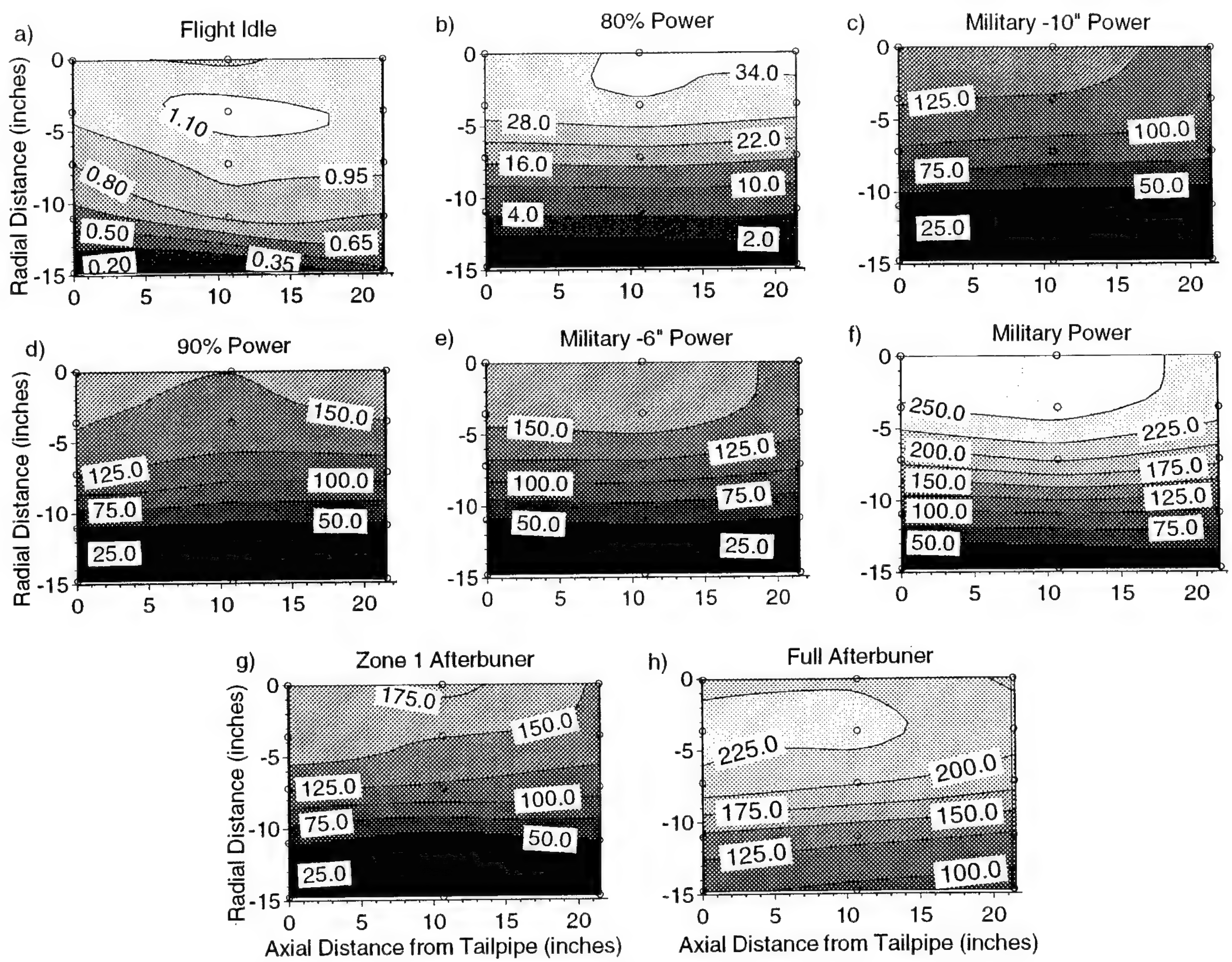


Figure 6. TF30-P111+ Contour Plots Showing Exhaust NO Concentration (ppm)

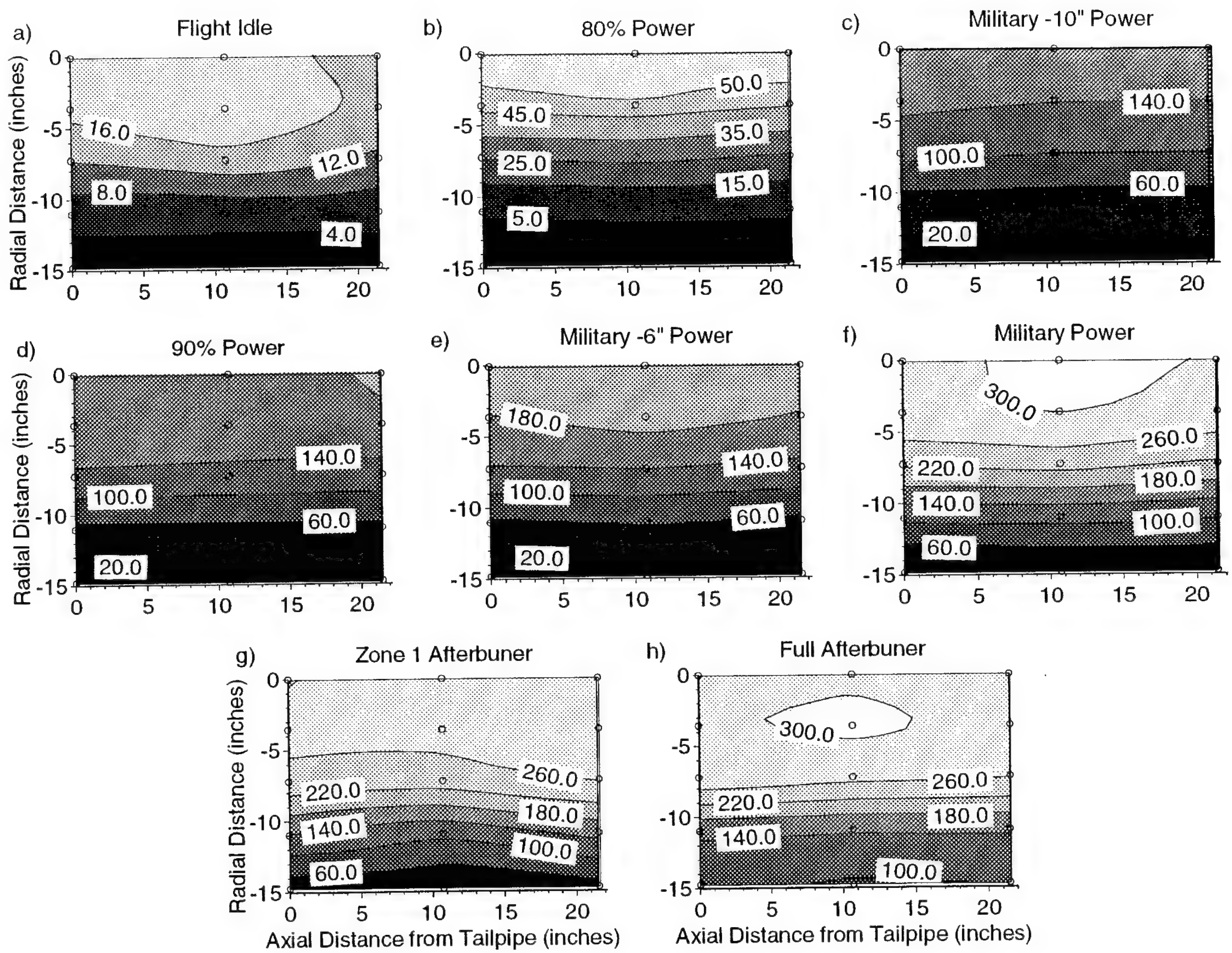


Figure 7. TF30-P111+ Contour Plots Showing Exhaust NOx Concentration (ppm)

TABLE 2. TF30-P111+ EXHAUST CHARACTERISTICS

Throttle Setting	Area-Weighted Average NO (ppm)	NO$_x$ (ppm)	CO (ppm)	Temp. (°F)	Normalized NO Index (lb/k-lb fuel)	NO$_x$ Index (lb/k-lb fuel)
Flight Idle	0.8	7.4	242	328	0.01	0.14
80% Power	9.9	14.6	88.4	353	0.20	0.29
Military -10" Power	52.0	60.7	61.2	547	0.62	0.72
90% Power	67.9	75.6	73.1	594	0.72	0.79
Military -6" Power	71.6	79.8	63.3	599	0.74	0.81
Military Power	125.2	137.2	74.6	723	0.92	1.00
Zone 1 AB	77.7	173.1	1121.0	1264	0.37	0.87
Full Afterburner	153.0	182.7	66376.3	2792	0.11	0.13

flow rates, while little change is seen in emissions output. The normalized indexes also indicate the significance of NO_2 in the plume. Nitrogen dioxide appears to make up from 5 to 30 percent of the total NO_x seen in the exhaust with peak levels of 57 percent at Zone 1 afterburner. No evaluation was made of conversion of NO to NO_2 or NO_2 to NO in the probe.

The P9 engine shows similar NO/ NO_x trends to the P111+ through its power band. Figures 8 and 9 show that NO_2 makes up 10 to 30 percent of the total NO_x. One difference seen here is the peak point values at each power setting occur toward the wall of the nozzle located at radial position Z = -12 inches. Unlike the P111+, most of the bypass fan air is directed around the engine case, leaving mostly the exhaust products in the center of the plume. The degree of dilution and mixing that occurs before the converging nozzle results in the distribution of points seen at the exit plane.

The P9 exhaust stream does show signs of dilution over the sampling area, but the degree of dilution is not significant. Table 3 shows a 70 percent jump in the area-weighted NO_x emissions from part power to military power, but the 88 ppm NO_x peak emissions value is about half as much as that for the P111+ engine.

B. CO EMISSIONS

The carbon monoxide data illustrated in Figure 10 (P111+) and in Table 3 (P9) show a similar trend as described in the Background; as engine speed increases towards military power, CO concentrations decrease. Abnormalities in the midpoint contours seen in Figures 10d-f have very little deviation (about 5 ppm - 6 percent error) and cannot be confirmed within the

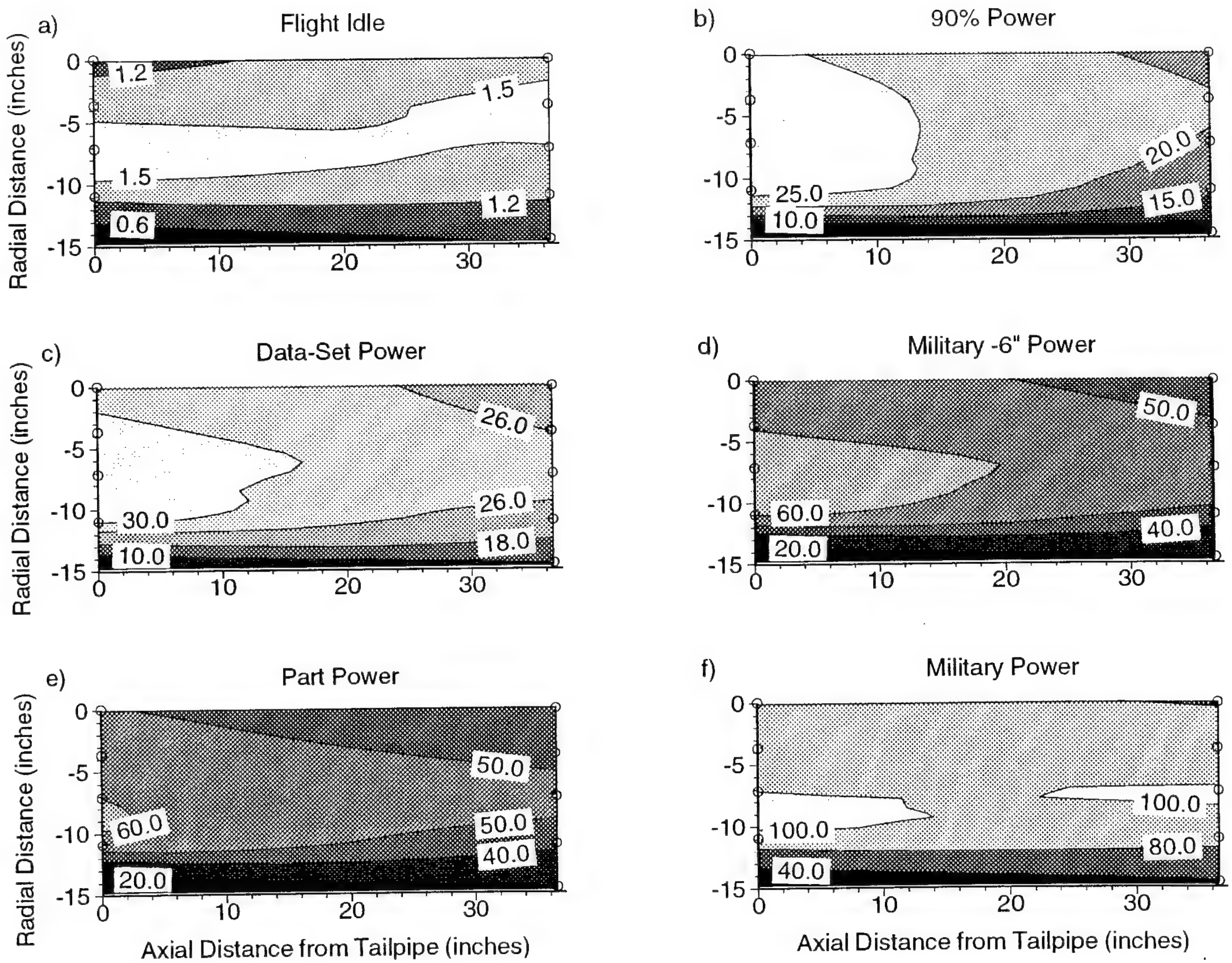


Figure 8. TF33-P9 Contour Plots Showing Exhaust NO Concentration (ppm)

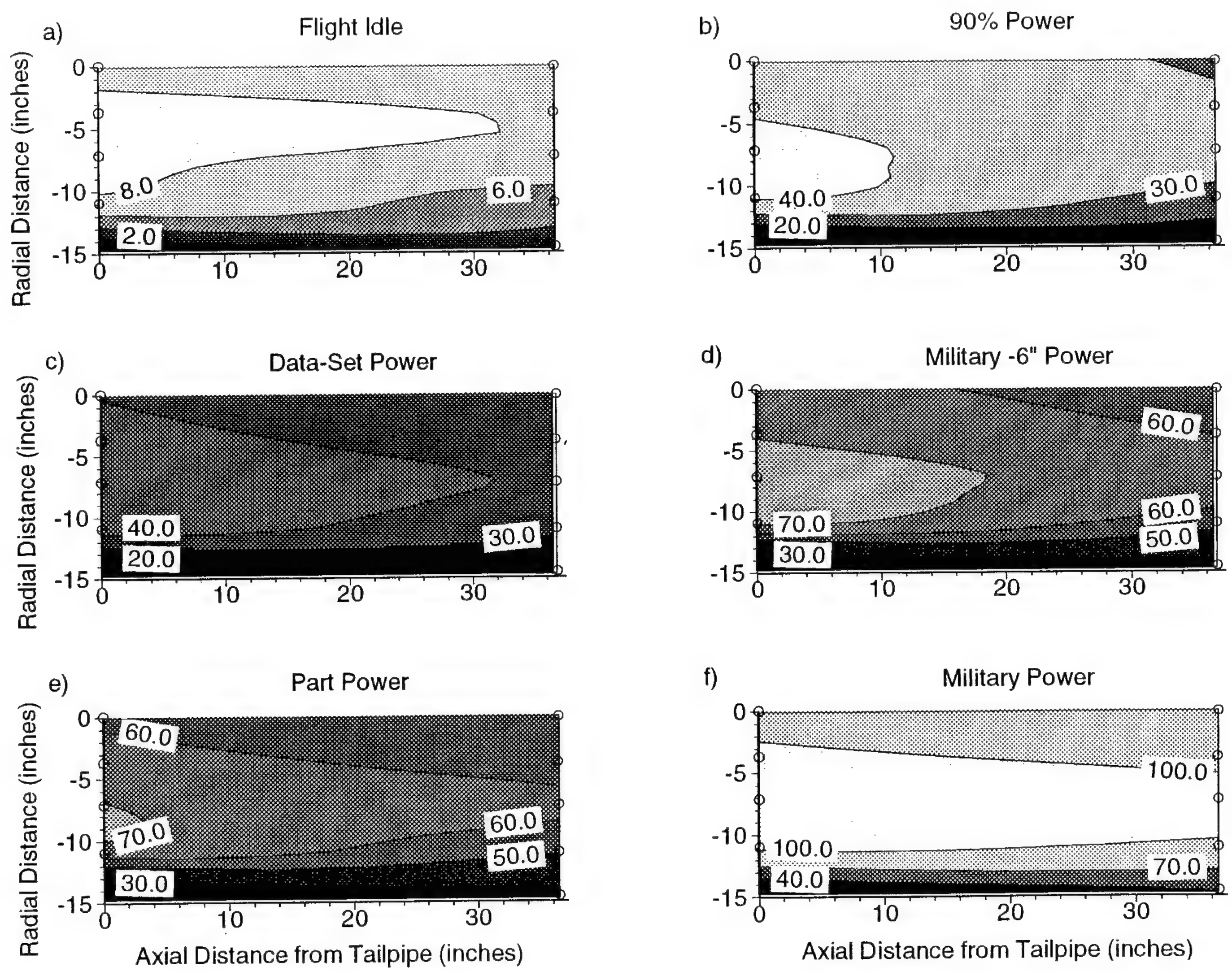


Figure 9. TF33-P9 Contour Plots Showing Exhaust NOx Concentration (ppm)

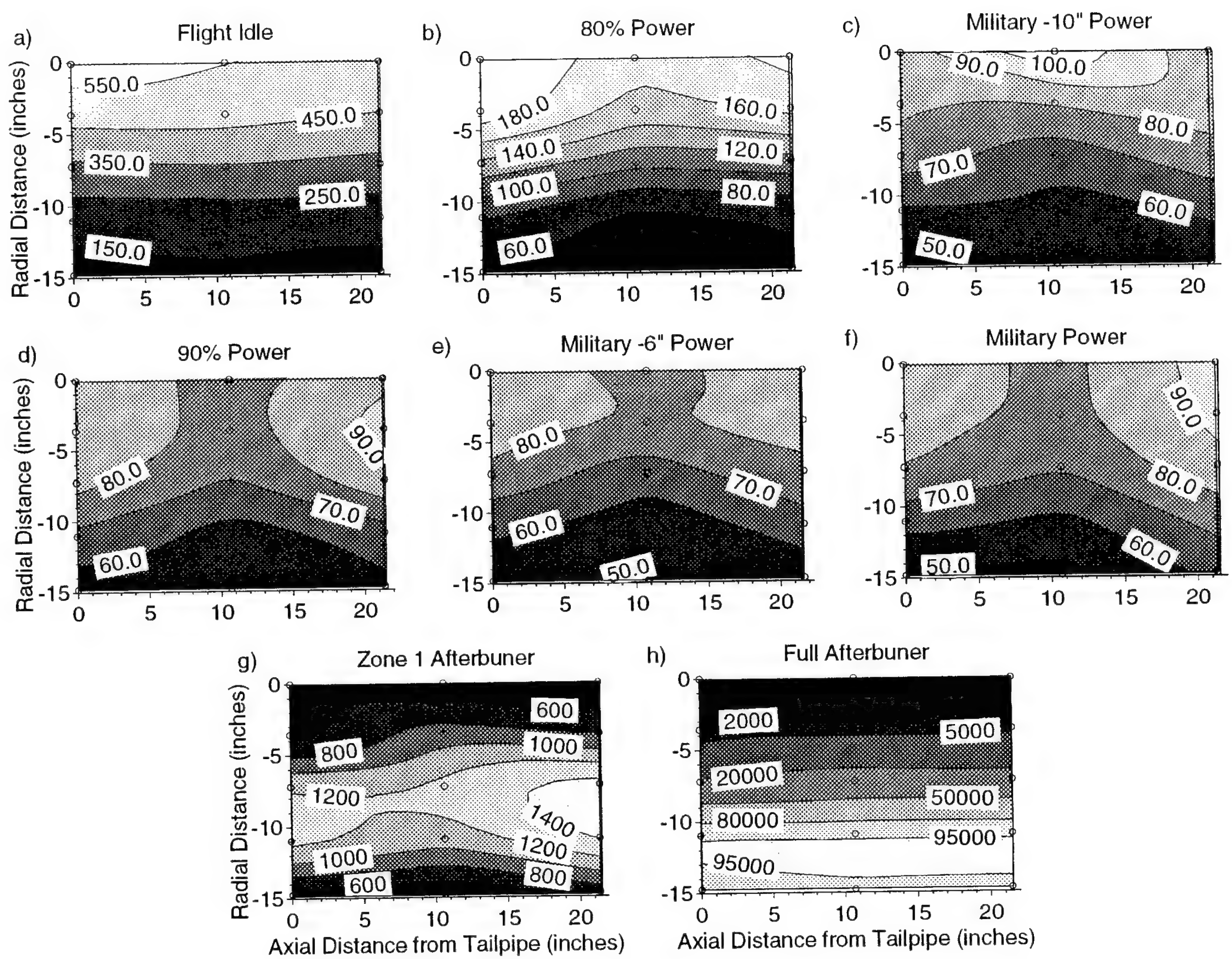


Figure 10. TF30-P111+ Contour Plots Showing Exhaust CO Concentration (ppm)

the hotter-burning P111+. However, the P9's area-weighted average temperature at military power is 95°F higher than at military power on the P111+.

D. RUN-TIME NO AND NO_X

Based upon the emissions at each position, the approximate weight of NO and NO_x was calculated using the method shown in Appendix B. The values were then divide through by the highest value to produce the normalized NO and NO_x values found in Table 4. Military power is by far the largest offender, producing 50 percent of the total NO_x and 46 percent of the NO emitted from the JETC during a full testing period. The next highest offenders produce only one quarter of military power NO_x values. Over 95 percent of the total NO_x emitted is produced between Military -10 inches power and full afterburner settings. Seventy-five percent of all NO and NO_x emissions are produced from military power to full afterburner. Since temperatures are

TABLE 4. NORMALIZED NO/ NO_X PRODUCTION PER TF30-P111+ RUN

	Total Time (min.)	Fuel Usage (lb.)	Normalized NO	Normalized NO_x
Flight Idle	17	326	0.00	0.03
80% Power	3	155	0.02	0.03
Military -10" Power	3	327	0.13	0.15
90% Power	3	354	0.16	0.17
Military –6" Power	3	370	0.17	0.19
Military Power	10.25	1606	0.92	1.00
Zone 1 Afterburner	2	465	0.11	0.25
Zone 5 Afterburner	3.5	3138	0.21	0.25
Totals	44.75	6741	1.72	2.07

high this appears to be the area of application for an effective NO_x control method.

SECTION IV
CONCLUSIONS

The overall focus of this program is on NO and NO_x and its possible reduction. Knowing the exhaust effluent characteristics is important to optimizing a NO_x control strategy. It is therefore essential to characterize the entire plume as completely as possible, including the species and characteristics. Several general conclusions can be drawn about both the TF30-P111+ and the TF33-P9 engine exhaust flow fields:

- Power setting of the engine makes a significant impact on the NO and NO_x produced.
- Dilution is noticeable but not significant in the exhaust free stream between the tailpipe exit and the augmenter.
- NO_2 makes up 10 to 30 percent of the total NO_x flow field.
- Carbon monoxide decreases with increasing power for the non-after-burning settings.

The afterburning P111+ engine is by nature a high-performance, "hot"-burning engine, making its characteristics particularly interesting for the application of SNCR. The following conclusions can be drawn based upon the results of the TF30 P111+ engine:

- Zone 1 afterburner NO and NO_x emissions dip from those at military power possibly due to a reburning and/or dilution effect. However, NO_2 appears to make up a significant fraction (up to 50 percent) of the NO_x emissions.
- Levels of CO increase dramatically in the afterburner regions with peak values in excess of 10 percent. CO peak levels also shift radially outward due to the afterburner spray-bar geometry.
- Peak temperatures range from 1100°F at military power to over 2800°F at full afterburner. Peak afterburner temperatures shift with the peak CO levels.
- An area-weighted index for NO_x reveals military power is the highest polluter during a typical engine run. Power settings between Military -10 inches and Zone 1 afterburner comprise 90 percent of the total NO_x produced.

The non-afterburning, high bypass TF33-P9 engine exhaust characteristics differ in the following ways:

- The narrow exhaust duct and lack of fan bypass air create a more even distribution of emissions and temperatures through the exhaust nozzle.
- Peak NO_x values reach 117 ppm at military power, almost a third less than the P111+.
- Average temperatures at military throttle are almost 900°F, 95°F more than military power average for the P111+.

The results are promising for at least 75 percent of the NO_x produced by the P111+. Settings from military power through full afterburner have temperatures that might apply themselves to SNCR. High amounts of CO also make this attractive for application. Although the TF33-P9 engine does offer a higher average temperature at military power, the lower peak temperatures and CO concentrations at full power make the application of SNCR more challenging for this engine. Each SNCR application will be engine- and cell-type- specific.

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APPENDIX A
ENGINE EXHAUST VALUES

Appendix A lists the average exhaust emission point values used to create Figures 6-11. These were found by averaging the various data taken from different engines at similar throttle positions and sampling points. The probe column shows the measurements made (0.0 inches is centerline, -14.75 inches is the outer edge of the sampling area). NO, NO_x, CO, and HC emission values are tabulated in parts per million (ppm). The values of O_2 and CO_2 measured with the gas chromatograph (GC) are listed in percents. MEXA O_2 values are also listed as a redundant measurement of the GC. The pitot probe readings were taken at the centerline of the flow to help determine the residence time for SNCR applications at the various throttle settings.

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 0.0"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Flight Idle Average	0.00	1.0	16.1	493.4	599	11	20.00	1.09	17.78	887
	-3.63	1.0	17.1	434.7	613	8	20.22	1.09	17.97	
	-7.31	0.8	12.0	306.8	532	6	20.89	1.30	18.63	
	-11.00	0.6	5.1	168.9	291	2	21.32	0.93	19.43	
	-14.75	0.2	2.0	90.8	159	1	22.03	0.36	19.93	
80% Power Average	0.00	32.2	51.4	206.2	782	6	18.86	2.08	17.62	1361
	-3.63	32.2	49.3	196.4	758	4	19.07	1.94	17.86	
	-7.31	16.8	24.9	134.4	648	2	20.50	1.10	19.17	
	-11.00	3.2	4.6	78.8	286	2	21.65	0.24	20.41	
	-14.75	0.2	0.7	52.5	126	2	22.05	0.14	20.64	
Military -10" Power Average	0.00	129.9	150.2	85.0	952	0	18.26	3.12	17.40	1996
	-3.63	130.3	151.9	82.3	960	0	18.21	3.17	17.46	
	-7.31	97.4	112.3	75.3	845	0	19.14	2.20	18.24	
	-11.00	31.8	36.6	58.6	499	0	20.97	0.83	19.95	
	-14.75	2.7	3.7	41.1	305	0	22.13	0.11	20.75	
90% Power Average	0.00	154.8	177.9	88.5	979	2	18.17	2.17	16.87	2019
	-3.63	153.0	177.5	91.1	974	0	18.06	2.18	17.01	
	-7.31	134.5	133.6	83.2	881	0	18.53	1.47	17.86	
	-11.00	43.2	49.1	67.4	524	0	19.29	0.54	19.66	
	-14.75	4.6	6.4	54.2	217	0	21.78	0.14	20.55	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 0.0"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Military -6" Power Average	0.00	158.0	182.3	85.0	999	0	17.94	2.90	17.36	2068
	-3.63	159.9	184.1	86.7	1016	0	17.74	2.96	17.39	
	-7.31	120.7	139.1	77.1	904	0	18.94	2.21	18.20	
	-11.00	43.7	51.0	62.1	561	0	20.87	0.95	19.91	
	-14.75	4.7	6.1	52.5	323	0	22.12	0.20	20.65	
Military Power Average	0.00	246.7	283.3	89.4	1107	0	17.96	2.40	16.64	2172
	-3.63	249.4	287.4	89.4	1123	0	16.64	3.65	16.71	
	-7.31	180.0	227.3	84.1	1019	0	19.02	1.80	17.57	
	-11.00	92.3	106.2	69.6	680	0	20.94	0.89	19.29	
	-14.75	11.4	14.0	54.2	326	0	21.17	0.16	20.53	
Zone 1 Afterburner Average	0.00	161.3	258.1	471.4	1173	70	16.68	3.61	16.68	2688
	-3.63	172.0	271.1	473.5	1218	52	16.93	4.14	16.25	
	-7.31	129.7	249.8	1239.7	1602	26	14.28	4.38	14.31	
	-11.00	48.4	135.8	1326.7	1623	70	16.54	3.78	15.71	
	-14.75	5.0	35.5	529.8	772	44	20.48	1.23	19.42	
Full Afterburner Average	0.00	220.6	285.8	1079.4	2287	12	10.75	7.28	11.46	2748
	-3.63	231.4	299.0	837.0	2445	16	9.23	8.30	9.61	
	-7.31	222.9	297.8	16839	2905	98	2.95	12.14	5.47	
	-11.00	139.8	139.8	103450	2840	340	0.00	9.07	3.84	
	-14.75	104.2	111.5	86900	2883	130	0.00	9.46	3.60	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 10.75"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Flight Idle Average	0.00	2.0	15.9	559.0	536	24			17.19	210
	-3.63	2.7	15.7	494.6		22			17.67	
	-7.31	3.7	12.6	347.1		20			18.37	
	-11.00	0.7	3.7	197.4	269	16			19.26	
	-14.75	0.0	2.1	141.5		14			19.82	
80% Power Average	0.00	34.6	53.5	164.5	751	10	18.55	2.32	18.21	1122
	-3.63	35.0	51.4	153.8	743	10	17.97	2.10	18.28	
	-7.31	18.2	27.2	104.8	583	8	19.25	1.22	18.93	
	-11.00	3.3	5.6	52.0	257	6	21.47	0.28	19.83	
	-14.75	0.5	1.2	44.2	112	8	20.87	0.07	20.25	
Military -10" Power	0.00	130.4	148.8	108.7	929					
	-3.63	127.2	144.8	79.7						
	-7.31	87.7	102.1	63.9						
	-11.00	29.5	34.4	56.0						
	-14.75	3.8	5.3	53.4						
90% Power Average	0.00	149.7	174.7	75.7	968	10	17.33	2.99	17.72	2070
	-3.63	144.4	172.8	75.7	966	8	17.45	2.49	17.60	
	-7.31	110.5	127.6	69.2	840	6	19.07	1.82	18.15	
	-11.00	41.0	48.2	54.7	479	4	20.75	0.65	19.26	
	-14.75	5.1	7.3	50.7	189	6	21.29	0.15	20.02	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 10.75"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC		MEXA	Pitot ft/sec
							O_2 %	CO_2 %	O_2 %	
Military -6" Power	0.00	166.1	201.8	77.1	989					
	-3.63	169.5	199.0	79.7						
	-7.31	120.5	143.5	63.9						
	-11.00	52.6	60.6	53.4						
	-14.75	7.5	10.0	48.1						
Military Power Average	0.00	268.0	313.9	76.2	1123	10	18.58	3.06	17.22	2502
	-3.63	264.0	309.1	77.1	1124	6	18.21	3.83	17.17	
	-7.31	200.2	235.6	68.3	1026	8	19.11	2.46	17.58	
	-11.00	98.0	112.7	57.7	657	6	21.69	1.03	18.81	
	-14.75	14.6	19.8	46.4	271	4	22.62	0.25	19.97	
Zone 1 Afterburner Average	0.00	185.4	285.3	398.7	1176					2613
	-3.63	149.7	273.2	918.6						
	-7.31	125.2	242.5	1303.6						
	-11.00	26.4	98.4	1106.5						
	-14.75	4.5	26.6	417.8						
Full Afterburner Average	0.00	221.9	295.1	1112.1	1163	20	12.43	6.34	13.13	
	-3.63	237.1	309.0	691.9	2414	14	10.26	7.93	11.42	
	-7.31	207.3	279.8	25600	2960	54	2.09	11.91	7.98	
	-11.00	128.4	131.9	102000	2844	256		8.03	5.95	
	-14.75	94.4	95.3	93300		146		9.26	5.23	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 21.5"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Flight Idle Average	0.00	2.0	15.0	509.8	561	21	20.17	1.34	17.92	868
	-3.63	1.3	14.1	453.9	591	18	20.22	1.74	18.11	
	-7.31	1.5	10.3	321.8	483	14	21.05	0.85	18.60	
	-11.00	0.4	4.2	198.2	254	11	21.72	0.43	19.21	
	-14.75	0.3	2.1	121.6	164	9	21.98	0.19	19.54	
80% Power Average	0.00	35.6	53.6	192.5	714	6	19.92	2.08	17.61	1360
	-3.63	32.6	47.8	174.2	744	6	19.41	1.76	17.87	
	-7.31	16.1	23.1	117.1	553	3	20.60	0.94	18.97	
	-11.00	3.6	4.9	64.8	231	2	21.09	0.26	19.66	
	-14.75	1.0	1.6	59.9	109	4	21.82	0.11	20.25	
Military -10" Power Average	0.00	120.9	147.5	82.3	896	6	18.10	2.52	17.16	1987
	-3.63	118.3	144.6	84.5	935	6	18.38	2.44	17.25	
	-7.31	83.0	102.1	77.6	798	4	19.34	1.69	18.07	
	-11.00	29.3	35.1	62.3	451	3	20.72	0.59	19.35	
	-14.75	7.8	9.3	53.4	212	2	21.21	0.16	19.96	
90% Power Average	0.00	159.8	183.1	109.5	966	4	18.16	2.67	16.85	2059
	-3.63	153.8	179.4	94.0	980	3	18.34	2.59	17.00	
	-7.31	111.2	125.3	88.7	880	2	19.55	1.79	17.94	
	-11.00	42.9	51.0	64.9	488	2	21.29	0.73	19.29	
	-14.75	12.2	9.4	58.0	202	3	21.45	0.23	20.03	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF30-P111+
Axial Position: 21.5"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Military -6" Power Average	0.00	150.7	185.8	85.0	949	5			17.09	2114
	-3.63	149.7	183.7	83.4	989	5	18.53	2.55	17.11	
	-7.31	108.6	131.9	78.1	864	3	19.15	1.72	17.91	
	-11.00	41.9	49.6	65.5	505	2			19.24	
	-14.75	14.8	13.0	66.7	236	4	22.20	0.23	19.98	
Military Power Average	0.00	247.0	295.9	94.6	1031	4	17.39	2.89	16.51	2171
	-3.63	246.6	288.8	92.9	1122	3	18.30	2.89	16.58	
	-7.31	187.3	217.3	86.7	1063	3	18.81	2.70	17.43	
	-11.00	90.5	99.2	74.4	634	4	20.56	1.30	18.89	
	-14.75	29.3	27.5	63.2	279	3	21.36	0.35	19.82	
Zone 1 Afterburner Average	0.00	146.8	266.1	430.1	928	176	18.20	2.04	16.55	2510
	-3.63	115.6	205.5	316.3	1205	87	17.11	4.04	16.14	
	-7.31	60.1	128.4	602.7	1472	63	17.51	2.79	15.02	
	-11.00	137.1	243.3	581.9	1515	89	18.65	2.24	15.72	
	-14.75	140.0	269.0	301.6	777	81	21.80	0.71	18.09	
Full Afterburner Average	0.00	195.2	277.8	828.8	2356	33	13.86	4.37	11.62	2812
	-3.63	121.0	222.9	1918.0	2460	22	11.64	5.20	10.01	
	-7.31	99.8	184.0	22834	2974	71	2.08	12.01	5.80	
	-11.00	119.4	200.8	102400	2785	268	0.00	8.26	4.47	
	-14.75	105.0	217.2	92700	2814	162	0.00	8.26	4.11	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF33-P9
Axial position: 0.0"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Flight Idle Average	0	1.1	7.6	754.1	504	84			19.17	170
	-3.63	1.35	8.4	848.7	451	93			19.13	
	-7.31	1.70	8.6	725.2		118			19.06	
	-11	1.40	8.2	644.5	472	93			19.14	
90% Power Average	0	25.9	36.0	81.0	640	29			18.74	1157
	-3.63	27.70	38.5	78.4	627	27			18.58	
	-7.31	28.50	43.9	98.2		27			18.38	
	-11	30.50	45.9	95.5	654	25			18.34	
Dataset Power	0.00	28.5	39.6	77.1	646	22			18.74	1166
	-3.63	31.2	42.5	63.9	630	22			18.58	
	-7.31	31.7	47.6	92.9		24			18.38	
	-11.00	34.1	49.0	95.5	655	20			18.34	
Military -6" Power	0.00	55.0	63.7	53.4	749	36			18.29	1469
	-3.63	59.0	68.9	50.7	760	32			18.17	
	-7.31	66.1	77.4	53.4		32			17.93	
	-11.00	67.5	79.7	53.4	754	26			17.77	
Part Power Average	0	50.4	58.4	50.7	740	31			18.35	1449
	-3.63	54.45	63.4	48.1	755	30			18.23	
	-7.31	60.85	71.3	57.3		29			17.98	
	-11	61.30	72.5	61.3	747	27			17.87	
Military Power	0.00	85.5	94.5	50.7	851	30			17.96	1654
	-3.63	90.9	102.6	48.1	854	26			17.81	
	-7.31	101.0	112.0	50.7		26			17.53	
	-11.00	105.7	117.7	50.7	867	26			17.34	

ENGINE EXHAUST VALUES (CONT.)

Engine: TF33-P9
Axial position: 36.5"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Flight Idle Average	0	1.4	7.6	845.8	474	108	19.59	1.33	20.29	147
	-3.63	1.63	8.0	901.7	468	114	19.85	1.40	20.23	
	-7.31	1.50	7.9	890.2	477	107	19.21	1.32	20.30	
	-11	1.30	4.9	582.1	391	80	20.46	0.87	20.69	
	-14.75	0.70	3.2	344.4	253	61	20.90	0.45	20.75	
90% Power	0.00	18.4	29.0	129.9	603	28			19.78	1124
	3.63	20.5	31.1	116.7	607	28			19.66	
	7.31	19.8	35.2	143.2	611	28			19.52	
	11.00	17.2	28.1	127.3	595	26			19.84	
	14.75	6.8	11.2	77.1	354	24			20.56	
Dataset Power	0.00	24.7	33.5	106.1		30			19.70	1244
	3.63	25.6	35.5	108.7	647	28			19.51	
	7.31	28.7	40.3	129.9	642	28			19.27	
	11.00	24.2	34.6	108.7	633	28			19.54	
	14.75	9.4	14.1	79.7	383	26			20.38	
Part Power Average	0	44.4	52.0	83.7	721	38	19.71	2.36	19.37	1479
	-3.63	46.80	55.1	81.0	725	26	19.74	2.30	19.41	
	-7.31	54.25	63.8	82.3	733	28	19.92	2.32	18.99	
	-11	45.00	53.5	82.3	723	25	20.09	2.01	19.26	
	-14.75	18.30	22.5	73.2	473	24	21.11	0.90	20.18	

ENGINE EXHAUST VALUES (CONT.)

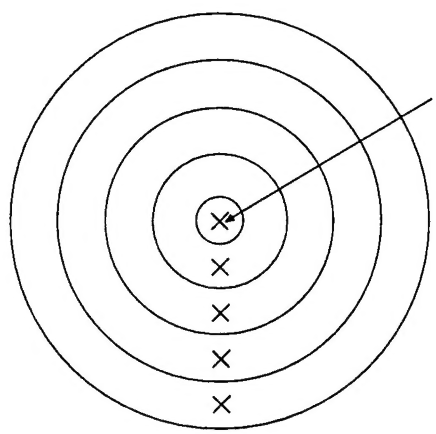
Engine: TF33-P9
Axial position: 36.5"

Throttle Setting	Probe inches	NO ppm	NO_x ppm	CO ppm	Temp °F	HC ppm	GC O_2 %	GC CO_2 %	MEXA O_2 %	Pitot ft/sec
Military -6" Power	0.00	46.1	55.2	85.0		18	18.68	1.58	19.17	1445
	3.63	50.2	59.2	85.0	647	18	18.47	1.45	19.10	
	7.31	58.1	66.9	95.5	642	36	18.57	2.76	18.83	
	11.00	49.9	57.9	92.9	633	32	18.94	2.45	18.98	
	14.75	18.7	23.2	77.1	383	30	20.24	1.00	20.13	
Military Power	0.00	78.5	86.5	82.3	870	28	19.86	2.39	18.84	1760
	3.63	90.1	93.9	79.7	888	26	19.42	3.10	18.70	
	7.31	103.1	108.6	82.3	877	22	19.07	2.28	18.38	
	11.00	94.5	102.5	79.7	897	22	18.35	2.21	18.36	
	14.75	35.3	39.3	69.2	594	20	20.32	0.89	19.82	

APPENDIX B

CALCULATIONS

To reduce the two-dimensional flow seen in the sample plane, the following procedure was used. Assuming radial uniformity, the values at each spatial location were averaged. These averages were used as the values for each annulus as shown below (the spacing between probes is 3.68 inches). Each of the five values were multiplied by the area of its annulus, the resulting values were added together, and the sum was divided by the total area, which resulted in the desired area-weighted average.



To standardize NO and NO_x values further, an index was calculated using the area-weighted averages to form an NO/NO_x production index (Reference 14). This index is similar to a conventional emissions index. The emissions index nomenclature is not used, however, due to the fact that rigorous data validation through the use of mass balances was not completed for the reasons described in the report. The intention of this calculation was to find the relative pollution levels for each of the throttle positions using area-weighting.

The formulas used to calculate the NO and NO_x indexes are the following:

$$\text{NO Index} = \left(\frac{[NO]}{[CO]+[CO_2]+[HC]} \right) * \left(\frac{1000 * M_{NO_2}}{M_C + \alpha M_H} \right) * \left(1 + T * \left(\frac{X}{m} \right) \right)$$

$$\text{NO}_x \text{ Index} = \left(\frac{[NO_x]}{[CO]+[CO_2]+[HC]} \right) * \left(\frac{1000 * M_{NO_2}}{M_C + \alpha M_H} \right) * \left(1 + T * \left(\frac{X}{m} \right) \right)$$

where

m, n	=	molecular constants for fuel, C_mH_n
$[x]$	=	mole fraction of species x (*e.g.*, *NO*, *CO*, etc.) in exhaust
M_x	=	atomic weight of species x
α	=	(atomic) hydrogen-carbon ratio of fuel = n/m
T	=	mole fraction of carbon dioxide in dry inlet air = 0.00032
X	=	moles of dry air per mole of fuel

Sample Calculation

The following conditions exist for the TF30-P111+ engine at military power assuming JP-8 fuel ($C_{10.9}H_{20.9}$):

NO	=	104.7 ppm
CO	=	74.6 ppm
CO_2	=	13651 ppm
HC	=	5 ppm
Total airflow	=	257 lb/sec
Fuel flow rate	=	9402 lb/hr
M_C	=	12.011
M_H	=	1.008
M_{NO2}	=	46.005
M_{air}	=	28.965
M_{fuel}	=	151.700

Solving for the variables in the NO Index equation, we find:

$$\alpha = 20.9/10.9 = 1.917$$

$$X = \left(\frac{151.7}{28.965}\right) * \left(\frac{\text{airflow lb / sec}}{\text{fuelflow lb / hr}}\right) * (3600\text{ sec / hr}) = 18225 * \left(\frac{\text{airflow lb / sec}}{\text{fuelflow lb / hr}}\right)$$

Therefore,

$$\textbf{NO Index} = \left(\frac{[104.7]}{[74.6]+[13651]+[5]}\right) * \left(\frac{1000*46.005}{12.011+1.917*1.008}\right) * \left(1+0.00032*\left(\frac{18225*\left(\frac{257}{9402}\right)}{10.9}\right)\right)$$

$$= \textbf{25.5 lb NO/k-lb fuel}$$

These index values were used with fuel flow rates and estimated run time to produce emissions values for further evaluation. The actual numbers were divided through by the highest value to normalized the numbers. These numbers revealed the conditions that produce the most NO/NO_x during normal JETC operation.